

Broad band time-resolved $E_{p,i}$ – L_{iso} correlation in GRBs

F. Frontera^{1,2}, L. Amati², C. Guidorzi¹, R. Landi², J. in't Zand³

ABSTRACT

We report results of a systematic study of the broad band (2–2000 keV) time resolved prompt emission spectra of a sample of gamma-ray bursts (GRBs) detected with both Wide Field Cameras on board the *BeppoSAX* satellite and the *BATSE* experiment on board CGRO. In this first paper, we study the time-resolved dependence of the intrinsic peak energy $E_{p,i}$ of the $EF(E)$ spectrum on the corresponding isotropic bolometric luminosity L_{iso} . The $E_{p,i}$ – L_{iso} relation or the equivalent relation between $E_{p,i}$ and the bolometric released energy E_{iso} , derived using the time averaged spectra of long GRBs with known redshift, is well established, but its physical origin is still a subject of discussion. In addition, some authors maintain that these relations are the result of instrumental selection effects. We find that not only a relation between the measured peak energy E_p and the corresponding energy flux, but also a strong $E_{p,i}$ versus L_{iso} correlation are found within each burst and merging together the time resolved data points from different GRBs. We do not expect significant instrumental selection effects that can affect the obtained results, apart from the fact that the GRBs in our sample are sufficiently bright to perform a time-resolved spectroscopy and that they have known redshift. If the fundamental physical process that gives rise to the GRB phenomenon does not depend on its brightness, we conclude that the found $E_{p,i}$ versus L_{iso} correlation within each GRB is intrinsic to the emission process, and that the correlations discovered by Amati et al. and Yonetoku et al. are likely not the result of selection effects. We also discuss the properties of the correlations found.

Subject headings: gamma ray bursts: general — gamma rays: stars

¹Università di Ferrara, Dipartimento di Fisica, Via Saragat 1, 44100 Ferrara, Italy; email: frontera@fe.infn.it

²INAF, Istituto di Astrofisica Spaziale e Fisica Cosmica, Bologna, Via Gobetti 101, 40129 Bologna, Italy

³Space Research Organization in the Netherlands, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

1. Introduction

In spite of the major advances in knowledge of gamma-ray bursts (GRBs) afterglow properties, mainly made with *Swift*, the GRB phenomenon is still poorly understood (Lyutikov 2009). It is recognized that the study of the prompt emission is of crucial importance, as it is more directly connected with the original explosion. One of the issues still open is the radiation emission mechanism(s) at work. Most of the GRB properties derived thus far come from the time-averaged spectra. The function that has been found to better describe them from 15 keV up to 10 MeV is a smoothly broken power-law proposed by Band et al. (1993, *Band function*, BF). On the basis of the spectral data obtained with the *Burst and Transient Source Experiment* (*BATSE*), aboard the *Compton Gamma Ray Observatory* satellite (*CGRO*) and, for example, with the *BeppoSAX* GRBM data (e.g., Guidorzi et al. 2011), for long GRBs (>2 s), the mean value of the low-energy photon index α of the BF is about -1 , while that of the high-energy photon index β is about -2.3 (Kaneko et al. 2006). As a consequence of this result, the received power per unit logarithmic energy interval $EF(E)$ shows a peak value that, in the *BATSE* era, seemed to show a sharp Gaussian distribution around 200 keV. With the discovery of the X-ray flashes with *BeppoSAX*, later also found with *HETE-2*, *Swift*, and, now, with the *Fermi* Gamma-ray Burst Monitor, this distribution results in being much flatter (e.g., Kippen et al. 2003; Sakamoto et al. 2005). In the cases in which β cannot be constrained, a power-law model with a high energy exponential cutoff (CPL) gives a good fit to the data, and, in some cases, even a simple power-law can describe the GRB time averaged spectra up to several MeV photon energies (Kaneko et al. 2006).

Several radiative emission models have been worked out for the interpretation of the GRB spectra. Given their non-thermal shape, the first model proposed was synchrotron emission by non thermal electrons in strong magnetic fields (Rees & Meszaros 1994; Katz 1994; Tavani 1996). Indeed, the time-averaged spectra of many GRBs are consistent with an optically thin synchrotron shock model (e.g., Tavani 1996; Amati et al. 2001). However, there are a significant number of GRBs for which this model does not work. Indeed, while for an optically thin synchrotron spectrum, the expected power-law index of the $EF(E)$ spectrum below the peak energy E_p cannot be steeper than $4/3$ (ideal case of an instantaneous spectrum in which electron cooling is not taken into account), in many cases (e.g., Preece et al. 1998, 2000) the measured spectra, even those time resolved (Cridder et al. 1997; Frontera et al. 2000), are inconsistent with these expectations.

To overcome these difficulties, either modifications of the above synchrotron scenario (e.g., Lloyd & Petrosian 2000) or other radiative models (e.g., Liang et al. 1997; Blinnikov et al. 1999; Lazzati et al. 2000; Mészáros & Rees 2000; Stern & Poutanen 2004; Pe’er & Zhang 2006; Pe’er et al. 2007; Lazzati et al. 2009; Pe’er & Ryde 2011) have been suggested. Each

of these models interprets some of the prompt emission features, but fails to interpret others.

One of the GRB spectral properties that the emission models should interpret is the correlation between the intrinsic (redshift corrected) peak energy $E_{p,i}$ of the $EF(E)$ function and either the GRB released energy E_{iso} (Amati et al. 2002) or the peak bolometric luminosity $L_{p,\text{iso}}$ (Yonetoku et al. 2004). Both correlations (the Amati relation and the Yonetoku relation) have been derived from the time-integrated spectra assuming isotropic emission. The Yonetoku relation followed the Amati’s, from which the so-called Ghirlanda relation (Ghirlanda et al. 2004) was also derived by replacing the released energy E_{iso} with that (E_γ) corrected for the beaming factor ($E_\gamma = (1 - \cos\theta)E_{\text{iso}}$). The latter is model dependent, being derived assuming a jet like structure of the fireball, a constant efficiency of the fireball in converting kinetic energy in the ejecta into gamma rays, a mass density distribution of the circumburst medium, and, mainly, that the break time observed in the late afterglow light curve occurs when reciprocal of the bulk Lorentz factor of the jet, $1/\Gamma$, becomes of the order of the jet opening angle θ_{jet} . The latter assumption requires that the break time is achromatic, property not observed in many *Swift* GRBs (e.g., Campana et al. 2007; Melandri et al. 2008). In any case, these relations are all equivalent as far as the physics: a relation between the photon energy in which most of the energy is released and the electromagnetic radiation emitted by a GRB, which can be expressed equivalently in terms of released energy or peak (or average) GRB luminosity.

The Amati relation (Amati et al. 2008, $E_{p,i} = KE_{\text{iso}}^m$, with $K = 98 \pm 7$ and $m = 0.54 \pm 0.03$, where $E_{p,i}$ is measured in keV and E_{iso} is given in units of 10^{52} erg), is satisfied, within an extra-Poissonian scatter of $\log E_{p,i}$ normally distributed around the best-fit power-law with $\sigma \sim 0.2$ dex, by all long GRBs (more than 100) with known redshift z discovered thus far, except the nearest and least energetic GRB ($z = 0.0085$) ever observed (GRB 980425) and, maybe, GRB 031203 (e.g. Amati et al. 2007), but not by short GRBs. Also the Yonetoku relation is satisfied for GRBs with known redshift, except GRB 980425 (e.g., Ghirlanda et al. (2005b); Nava et al. (2012)), given the tight correlation found between $L_{p,\text{iso}}$ and E_{iso} (Ghirlanda et al. 2005b).

In spite of this, the Amati relation has been questioned by various authors (Band & Preece 2005; Butler et al. 2007, 2009; Shahmoradi & Nemiroff 2009; Collazzi et al. 2011), maintaining that it is likely the result of selection effects, even if these effects, when investigated by other authors (Ghirlanda et al. 2005a, 2008; Nava et al. 2008; Amati et al. 2009; Krimm et al. 2009; Nava et al. 2011) are found to be marginal.

One of the major criticisms of the Amati relation is that its normalization depends on instrument sensitivity (Butler et al. 2007). However, this conclusion by Butler et al. (2007) for *Swift* GRBs was not based on measured spectral peak energies $E_{p,i}$, but on $E_{p,i}$ values

inferred, under some assumptions, from a Bayesian method. An investigation, performed by Amati et al. (2009) by deriving the $E_{p,i}$ dependence on E_{iso} for different sets of GRBs, each obtained with a different instrument, and by using the measured values of $E_{p,i}$ reported in the *Swift* BAT official catalog by Sakamoto et al. (2008), has not confirmed the inferences by Butler et al. (2007).

Other works that question the reliability of the $E_{p,i} - E_{\text{iso}}$ make use of the (E_p , Fluence) observer plane, positioning in this plane the data points obtained from the spectral analysis of GRBs detected with different satellite instruments, using the method first proposed by Nakar & Piran (2005). While some authors (e.g. Band & Preece 2005; Goldstein et al. 2010) find that most of the long *BATSE* GRBs do not satisfy the relation, other authors (e.g., Ghirlanda et al. 2005a; Nava et al. 2008, 2011) find that most of them do. This discrepancy is due to various reasons, such as the condition assumed to satisfy or not satisfy the Amati relation and the systematic errors in the determination of fluence and E_p (e.g. Collazzi et al. 2011). However some results are well established and are shared by most authors who have performed the $E_{p,i} - E_{\text{iso}}$ test. GRBs with known redshift are not a special sub-population, they are evenly distributed along the weaker correlation between E_p and fluence (Ghirlanda et al. 2008; Collazzi et al. 2012). No evidence of evolution of the $E_{p,i} - E_{\text{iso}}$ correlation with the redshift is found (Ghirlanda et al. 2008; Nava et al. 2011). In the observer frame, after all the results obtained with *Swift* and *Fermi*, no bursts with large fluence and low/intermediate E_p have been found. They do not exist or should be very rare: Nothing prevents their detection. Instead, bursts with intermediate/high E_p and small fluence could be affected by instrumental selection effects, such as the minimum flux to trigger a GRB, the minimum fluence to fit its spectrum and constrain its E_p , and truncation effects related to the instrument passband (Lloyd et al. 2000). The case of *Swift* BAT is an example of instrument affected by truncation biases: In spite of its higher fluence sensitivity than *BATSE*, E_p can be accurately determined only if it has a value within or very close to its energy passband (15–150 keV). However, we find some results about the validity of the $E_{p,i} - E_{\text{iso}}$ relation untenable, such as the conclusion by Collazzi et al. (2012), who find that a significant fraction of the same GRBs with known redshift which have been used to derive the Amati relation do not satisfy their test. Clearly, their test condition (their so-called "Amati limit") in the (Fluence, E_p) plane is too restrictive. The same authors state that, while the Amati relation is the result of selection effects, the Ghirlanda relation is valid. Also, this statement is problematic, given that this relation is based on the same E_p and Fluence measurements, being the only correction performed with, as discussed above, the replacement of E_{iso} with E_γ . In addition, the "Ghirlanda limit" is derived using rather loose assumptions about the beaming angle.

The opposite conclusion was recently reached by Yonetoku et al. (2010) via analyzing in

detail all possible data truncation and detector sensitivity effects, and by Nava et al. (2012), who analyzed a complete sample, for redshift determination, of bright *Swift* GRBs (1 s peak photon flux $P \geq 2.6$ photons s⁻¹ cm⁻² in the 15–150 keV BAT band).

From this long standing debate, it is apparent the need to explore other approaches for testing the origin of the spectrum–energy correlations, i.e., whether they are the result of instrumental selection effects or are related to the fundamental physics of the GRB phenomenon. Given the significant evolution of the GRB spectra, studies of time-resolved spectra are crucial not only to test the $E_{p,i}$ versus L_{iso} relation, but also to delve deeper into the issue of the radiative mechanisms at work during the prompt emission.

Motivated by both these needs, we performed a systematic study of the broad band (2–2000 keV) time–resolved prompt emission spectra of a sample of GRBs detected with both Wide Field Cameras (WFCs) aboard the *BeppoSAX* satellite and the *BATSE* experiment aboard the *CGRO*. In this paper we will concentrate on the test of the $E_{p,i}$ versus L_{iso} relation. The WFCs were among the few instruments that detected GRB prompt emission down to 2 keV. Thus we can obtain time-resolved spectra in an energy band still not well explored: the 2–2000 keV band. A paper devoted to testing physical emission models of GRBs using the same time-resolved spectra will be the subject of a forthcoming paper (Frontera et al. 2012, in preparation).

2. The GRB sample and spectral analysis

There were nine GRBs simultaneously detected with WFCs and *BATSE*: 970111, 971206, 971214, 980329, 980519, 990123, 990510, 990907, 991030. We performed an analysis of the prompt emission spectra of all of them. However, only four of them (970111, 980329, 990123, and 990510) were sufficiently bright to allow a fine time resolved spectroscopy (see Table 1).

The instrumentation that detected these bursts is widely described in the literature. For the *BATSE* experiment, see, e.g., Fishman et al. (1994), while, for WFC, see Jager et al. (1997). The *BATSE* spectra were taken from the Large Area Detectors (LADs), whose typical passband is 25–2000 keV. The LADs provide various types of data products. The data used for this analysis are the high energy resolution burst data, that provide 128 energy channels with a minimum integration time of 64 ms. For details of the *BATSE* spectral data products and detector response matrix see Kaneko et al. (2006, and references therein).

The WFCs consisted of two coded aperture cameras, each with a field of view of $40^\circ \times 40^\circ$ (full width at zero response) and an angular resolution of 5 arcmin. They operated in normal mode with 31 energy channels in 2–28 keV and 0.5 ms time resolution.

The background-subtracted light curves of the four strongest GRBs in our sample, detected with both *BATSE* and WFCs, are shown in Figure 1. For the *BATSE* data, the background level was estimated using the count rates immediately before and after the GRBs. Given that the background is variable during the GRB, it was estimated by means of a parabolic interpolation, channel by channel, between the background measured before the event and that measured after the event. For WFC spectra, the background level was estimated using an equivalent section of the detector area not illuminated by the burst or by other known X-ray sources. We also checked the consistency of this background level with that obtained by using the data before and after the burst.

We subdivided the time profile of each GRB into a number of time slices (see Figure 1), taking into account the GRB profile as observed with 1 s time resolution (visible pulses, their rise, peak, and decay) and the count statistics. We performed further spectral analysis in all of the time slices in which it was possible to constrain the peak energy E_p . With reference to Figure 1, in the case of GRB 970111 we excluded the first two (nos. 1 and 2) time slices for their low count statistics. For the same reason, we excluded from the analysis the first (no. 1) and the last (no. 8) of GRB 980329, the first (no. 1) of GRB 990123, and intervals 3, 4, 5, and 6 of GRB 990510. For this GRB, we also excluded intervals 13, 14 and 15, given that only an upper limit could be obtained for E_p . In the case of GRB 990123, we also excluded from the analysis the time intervals from 21 to 26, given that this part of the event was observed by WFC through the Earth’s atmosphere. The number of time intervals in which we subdivided the time profile of each event, the number of selected time slices in which it was possible to estimate and constrain E_p , the GRB fluence, and its redshift when known, are given in Table 1.

For each WFC+*BATSE* time resolved spectrum we used as an input model the BF:

$$N(E) = A \left(\frac{E}{100 \text{ keV}} \right)^\alpha \exp(-E/E_0)$$

if

$$(\alpha - \beta) \cdot E_0 \geq E$$

and

$$N(E) = A \left[\frac{(\alpha - \beta)E_0}{100 \text{ keV}} \right]^{\alpha - \beta} \exp(\beta - \alpha) \cdot \left(\frac{E}{100 \text{ keV}} \right)^\beta$$

if

$$(\beta - \alpha) \cdot E_0 \leq E$$

where α and β are the power law low-energy (below E_0) and high-energy (above E_0) photon indices, respectively, and A is the normalization parameter.

In the fit, along with A , α , and β , we adopted as a free parameter, instead of E_0 , the photon peak energy $E_p = E_0(2+\alpha)$. In addition, a normalization factor between *BATSE* and WFC data was included in the fit and left to vary in the range 0.8–1.2, to take into account a possible intercalibration error. Actually, we found that, for all analyzed GRB spectra, this parameter was consistent with 1. The systematic error used by the *BATSE* team to take into account the uncertainty in the background subtraction and the uncertainty in the instrument response function (see, e.g., Kaneko et al. (2006) for details) was injected in the fit.

The input model was assumed to be photoelectrically absorbed (WABS model in XSPEC). Given that the absorption column density N_H could not be constrained, a Galactic absorption along the GRB direction (Dickey & Lockman 1990) was assumed. To deconvolve the count rate spectra we adopted the XSPEC (*v. 12.5*) software package (Arnaud 1996). If not explicitly stated, the quoted uncertainties are single parameter errors at the 90% confidence level.

3. Results

The fit results of the BF to the joint WFC + *BATSE* time-resolved spectra of GRBs 970111, 980329, 990123 and 990510 are reported in Table 2. The time behavior of the best-fit parameters to the tested model is shown in Figure 2. In the bottom panels of this figure, the time behavior of the null hypothesis probability (NHP) is also shown.

From Figure 2 it is apparent that E_p , for each event, mimics the time behavior of the 2–2000 keV flux. This result is better shown in Figure 3, where the time-resolved peak energy derived from the best fit of BF to the time-resolved spectra is plotted as a function of the corresponding flux. As can be seen from this figure, a positive correlation is found for each of the four GRBs, consistent with a power-law dependence of the peak energy on flux, even if the statistical significance changes from one event to another, also depending on the number of available data points (see Table 3). The power-law parameters were derived in two ways: using the simple least-squares method, and the maximum likelihood method in the case that the correlated data (x_i, y_i) could be described by a linear function $Y = mX + q$ with the addition of an extrinsic (non Poissonian) variance σ_{ext}^2 among the free parameters (D’Agostini 2005). The latter method has already been adopted for various applications (see, e.g., Amati et al. (2008) and references therein).

Given that the peak energy E_p is related to both E_0 and α ($E_p = E_0(2 + \alpha)$), in order to establish the α contribution to the strong correlation between E_p and flux, we investigated the behavior of α with E_p . The result is shown in Figure 4. As can be seen, even if, in two cases (GRB 970111 and GRB 980329), we see a rapid change of α with E_p , no significant correlation is found in the cases of the other GRBs, especially in the case of GRB 990123, where we have the highest number of time-resolved spectra.

For GRBs with known redshift (GRB 990123 and GRB 990510), using the concordance cosmology ($\Omega_\lambda = 0.73$, $\Omega_m = 0.27$, $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$), we derived the intrinsic time resolved peak energy $E_{p,i}$ as a function of the corresponding 2–2000 keV isotropic luminosity L_{iso} . The result is shown in Figure 5. It does not change if we integrate L_{iso} up to 10 MeV using the best fit parameters of the BF. As can be seen from this figure, and quantified by the best fit correlation results (see Table 4), $E_{p,i}$ is related to L_{iso} through a power-law, with a very low probability that the result is due to chance, especially in the case of GRB 990123. For each of these GRBs, we also derived L_{iso} separately in the energy band below $E_{p,i}$ and above $E_{p,i}$. The result is that in both ranges the correlation between $E_{p,i}$ and L_{iso} still holds.

In order to see the cumulative result, we have merged all the available data on GRBs 990123 and 990510, to derive the mean dependence of $E_{p,i}$ on L_{iso} . The result is shown in Figure 6. A power-law dependence of $E_{p,i}$ on L_{iso} is still found (see Table 4), with a very low null hypothesis probability (1.57×10^{-13}), much lower than that found within each event, confirming the reality of the E_p – L_{iso} correlation in the single events.

4. Discussion and conclusions

By joining together the WFC and *BATSE* spectral data of the four strongest ($> 15 \times 10^{-6} \text{ erg cm}^{-2}$) GRBs simultaneously observed with both instruments, it was possible to perform a fine time-resolved spectral analysis in the broad energy band 2 keV to 2 MeV, a passband still scarcely explored as a whole.

We do not expect significant systematic errors from this joint analysis. The response functions of both instruments are well known. Indeed, in the fits the cross-calibration factor was found to be always 1, in spite of being left to vary between 0.8 and 1.2 (see Section 2). This is not the first time that a joint WFC/*BATSE* spectral analysis has been performed. Results of similar analyses have been reported in the past by the *BATSE* team (Briggs et al. 2000; Kippen et al. 2003, 2004). In addition, the *BATSE*–deconvolved spectra of bright GRBs were cross-checked with those obtained with *BeppoSAX* GRBM (Frontera et al. 2009); these in turn were cross-calibrated with WFC, with many published

results (e.g. Frontera et al. 1998, 2000).

For each of the strongest GRBs, we obtained a significant number of time-resolved spectra with constrained E_p : 8 spectra for GRB 970111, 6 spectra for GRB 980329, 19 spectra for GRB 990123, and 7 spectra for GRB 990510, with a total number of 40 analyzed spectra. With these spectra, we investigated the dependence of the time-resolved peak energy E_p on the corresponding 2–2000 keV flux using the empirical BF as an input model.

We find a significant power-law correlation between the derived peak energy E_p and the flux within each GRB in our sample. The power-law best-fit parameters, evaluated with two different methods (the least-squares method, and the likelihood method with the addition of an external variance as a free parameter) give (see Table 3) similar index values in the cases of GRBs 970111 (0.68 ± 0.06 versus $0.65^{+0.16}_{-0.14}$) and 980329 (0.16 ± 0.04 versus $0.15^{+0.08}_{-0.07}$), and different values in the case of the GRBs 990123 (0.53 ± 0.05 versus $0.46^{+0.09}_{-0.09}$) and 990510 (0.81 ± 0.15 versus $0.56^{+0.25}_{-0.23}$), even if, in the latter case, these values are statistically almost consistent with each other. However, the likelihood method has the advantage of giving us information about the non-Poissonian spread of the data points around the best-fit curve. It shows that such a spread, even if small, affects the correlation, with the highest value ($\sigma_{\text{ext}} = 0.09$ dex) in the case of GRB 990510 and the minimum one ($\sigma_{\text{ext}} = 0.00^{+0.04}_{-0.00}$ dex) in the case of GRB 980329. Actually, in this case, also due to the low statistics of the data points, the correlation significance is low and, as shown by the reduced χ^2 value (see Table 3), is not sensitive to an external spread.

No clear correlation is found between the low-energy photon index α and flux and between α and E_p , apart from in one case (GRB 980329). This means that the most relevant parameter that gives rise to the E_p –flux correlation is the break parameter E_0 in the BF.

An equivalent important result is that the power-law correlation found between E_p and flux is confirmed when we correlate, for two GRBs with known redshift, the intrinsic peak energy $E_{p,i}$ with the corresponding isotropic luminosity. Notice that the power-law index of the correlation changes from one GRB to the next when we use the least-squares method (0.53 ± 0.05 for GRB 990123, and 0.81 ± 0.15 for GRB 990510), but does not when the likelihood method is used (0.46 ± 0.09 for GRB 990123, $0.56^{+0.25}_{-0.23}$ for GRB 990510). This fact clearly means that the power-law index is affected by the external spread. If this spread is due to an unknown physical parameter, this result is an important hint for physical models of the prompt emission process: The intrinsic $E_{p,i}$ derived from the assumed emission model should be related to at least two physical parameters of the model.

When we join together all the available data on GRBs with known redshift we find that the $E_{p,i}$ – L_{iso} correlation becomes even more robust, with a probability of 1.57×10^{-13} that

the correlation averaged over all data is due to chance, and a power-law index that is almost independent of the used best fit method (0.66 ± 0.03 in the case of the least-square method versus $0.63^{+0.06}_{-0.07}$ in the case of the likelihood method). It is also interesting to note that the non-Poissonian spread found for the GRB averaged correlation ($\sigma_{\text{ext}} = 0.06^{+0.06}_{-0.05}$) is three times lower than the spread found in the Amati relation (Amati et al. 2009), which is well known to be based on time-averaged spectra. This is a strong hint that part of the spread of the Amati relation is related with the fact that the E_p values determined from time-averaged spectra are biased because of the spectral evolution of the GRB prompt emission.

If we compare our GRB-averaged correlation result with that obtained by Ghirlanda et al. (2010) from the time-resolved spectra of *Fermi* GRBs, we find that our results are consistent with those within a 2σ belt, even if the slope obtained by these authors (0.36 ± 0.05) is lower than that found by us ($0.63^{+0.06}_{-0.07}$; see Table 4 and Figure 6), likely due to the sample variance. Indeed, our found slope is similar to that (0.621 ± 0.003) reported by Lu et al. (2012), who performed the time-resolved spectral analysis of a sample of 15 *Fermi* GRBs with known redshift.

Within a 2σ spread, our results are also consistent with the time-averaged $E_{p,i}$ versus L_{iso} correlation, obtained by Ghirlanda et al. (2010) using 95 pre-*Fermi* plus 10 *Fermi* GRBs (see the right panel of Figure 7).

We cannot exclude that selection effects can influence our results, as with the fact that the analyzed GRBs are detected by both instruments, that they are sufficiently bright to allow time resolved analysis, and that they have known redshift. However, it seems difficult that this unavoidable selection can introduce a correlation between E_p and L_{iso} within single GRBs. In addition, a similar correlation has been found by the other mentioned authors (Ghirlanda et al. 2010; Lu et al. 2012) with other GRBs and with other instruments.

To conclude our results strongly support, at least in the range of luminosities explored with our data, the reality of the Amati (Amati et al. 2002) and the Yonetoku (Yonetoku et al. 2004) relations, both derived using time averaged spectra.

Also, our results give strong constraints on the physical models. In a forthcoming paper (Frontera et al. 2012, in preparation), with the same data we are testing different physical models, among them the recently developed GRBCOMP model, which is devoted to the spectral formation of a GRB (Titarchuk et al. 2012). In this model a physical interpretation of the Amati relation is also given.

We are grateful to Pawan Kumar for valuable discussions and suggestions. The *BepoSAX* satellite was a joint effort of the Italian Space Agency and the Netherland Space

Agency. This research made use of data obtained through the HEASARC Online service provided by the NASA Goddard Space Flight Center. We acknowledge its support.

REFERENCES

- Amati, L., Della Valle, M., Frontera, F., Malesani, D., Guidorzi, C., Montanari, E., & Pian, E. 2007, *A&A*, 463, 913
- Amati, L., Frontera, F., & Guidorzi, C. 2009, *A&A*, 508, 173
- Amati, L., Frontera, F., Tavani, M., in’t Zand, J. J. M., Antonelli, A., Costa, E., Feroci, M., Guidorzi, C., Heise, J., Masetti, N., Montanari, E., Nicastro, L., Palazzi, E., Pian, E., Piro, L., & Soffitta, P. 2002, *A&A*, 390, 81
- Amati, L., Frontera, F., Tavani, M., in’t Zand, J. J. M., Costa, E., Guidorzi, C., Montanari, E., & Soffitta, P. 2001, in *Gamma-ray Bursts in the Afterglow Era*, ed. E. Costa, F. Frontera, & J. Hjorth, 34
- Amati, L., Guidorzi, C., Frontera, F., Della Valle, M., Finelli, F., Landi, R., & Montanari, E. 2008, *MNRAS*, 391, 577
- Arnaud, K. A. 1996, in *Astronomical Society of the Pacific Conference Series*, Vol. 101, *Astronomical Data Analysis Software and Systems V*, ed. G. H. Jacoby & J. Barnes, 17
- Band, D., Matteson, J., Ford, L., Schaefer, B., Palmer, D., Teegarden, B., Cline, T., Briggs, M., Paciesas, W., Pendleton, G., Fishman, G., Kouveliotou, C., Meegan, C., Wilson, R., & Lestrade, P. 1993, *ApJ*, 413, 281
- Band, D. L., & Preece, R. D. 2005, *ApJ*, 627, 319
- Blinnikov, S. I., Kozyreva, A. V., & Panchenko, I. E. 1999, *Astronomy Reports*, 43, 739
- Briggs, M. S., Preece, R. D., van Paradijs, J., in’t Zand, J., Heise, J., Kuulkers, E., & Kouveliotou, C. 2000, in *American Institute of Physics Conference Series*, Vol. 526, *Gamma-ray Bursts, 5th Huntsville Symposium*, ed. R. M. Kippen, R. S. Mallozzi, & G. J. Fishman, 125–129
- Butler, N. R., Kocevski, D., & Bloom, J. S. 2009, *ApJ*, 694, 76
- Butler, N. R., Kocevski, D., Bloom, J. S., & Curtis, J. L. 2007, *ApJ*, 671, 656

- Campana, S., Guidorzi, C., Tagliaferri, G., Chincarini, G., Moretti, A., Rizzuto, D., & Romano, P. 2007, *A&A*, 472, 395
- Collazzi, A. C., Schaefer, B. E., Goldstein, A., & Preece, R. D. 2012, *ApJ*, 747, 39
- Collazzi, A. C., Schaefer, B. E., & Moree, J. A. 2011, *ApJ*, 729, 89
- Crider, A., Liang, E. P., Smith, I. A., Preece, R. D., Briggs, M. S., Pendleton, G. N., Paciesas, W. S., Band, D. L., & Matteson, J. L. 1997, *ApJ*, 479
- D’Agostini, G. 2005, *ArXiv e-prints*, 0511182v1
- Dickey, J. M., & Lockman, F. J. 1990, *ARA&A*, 28, 215
- Fishman, G. J., Meegan, C. A., Wilson, R. B., Brock, M. N., Horack, J. M., Kouveliotou, C., Howard, S., Paciesas, W. S., Briggs, M. S., Pendleton, G. N., Koshut, T. M., Mallozzi, R. S., Stollberg, M., & Lestrade, J. P. 1994, *ApJS*, 92, 229
- Frontera, F., Amati, L., Costa, E., Muller, J. M., Pian, E., Piro, L., Soffitta, P., Tavani, M., Castro-Tirado, A., Dal Fiume, D., Feroci, M., Heise, J., Masetti, N., Nicastro, L., Orlandini, M., Palazzi, E., & Sari, R. 2000, *ApJS*, 127, 59
- Frontera, F., Costa, E., Piro, L., Muller, J. M., Amati, L., Feroci, M., Fiore, F., Pizzichini, G., Tavani, M., Castro-Tirado, A., Cusumano, G., dal Fiume, D., Heise, J., Hurley, K., Nicastro, L., Orlandini, M., Owens, A., Palazzi, E., Parmar, A. N., in ’t Zand, J., & Zavattini, G. 1998, *ApJ*, 493, L67+
- Frontera, F., Guidorzi, C., Montanari, E., Rossi, F., Costa, E., Feroci, M., Calura, F., Rapisarda, M., Amati, L., Carturan, D., Cinti, M. R., Dal Fiume, D., Nicastro, L., & Orlandini, M. 2009, *ApJS*, 180, 192
- Ghirlanda, G., Ghisellini, G., & Firmani, C. 2005a, *MNRAS*, 361, L10
- Ghirlanda, G., Ghisellini, G., Firmani, C., Celotti, A., & Bosnjak, Z. 2005b, *MNRAS*, 360, L45
- Ghirlanda, G., Ghisellini, G., & Lazzati, D. 2004, *ApJ*, 616, 331
- Ghirlanda, G., Nava, L., & Ghisellini, G. 2010, *A&A*, 511, A43
- Ghirlanda, G., Nava, L., Ghisellini, G., Firmani, C., & Cabrera, J. I. 2008, *MNRAS*, 387, 319
- Goldstein, A., Preece, R. D., & Briggs, M. S. 2010, *ApJ*, 721, 1329

- Guidorzi, C., Lacapra, M., Frontera, F., Montanari, E., Amati, L., Calura, F., Nicastro, L., & Orlandini, M. 2011, *A&A*, 526, A49+
- Jager, R., Mels, W. A., Brinkman, A. C., Galama, M. Y., Goulooze, H., Heise, J., Lowes, P., Muller, J. M., Naber, A., Rook, A., Schuurhof, R., Schuurmans, J. J., & Wiersma, G. 1997, *A&AS*, 125, 557
- Kaneko, Y., Preece, R. D., Briggs, M. S., Paciesas, W. S., Meegan, C. A., & Band, D. L. 2006, *ApJS*, 166, 298
- Katz, J. I. 1994, *ApJ*, 432, L107
- Kippen, R. M., in’t Zand, J. J. M., Woods, P. M., Heise, J., Preece, R. D., & Briggs, M. S. 2004, in *American Institute of Physics Conference Series*, Vol. 727, *Gamma-Ray Bursts: 30 Years of Discovery*, ed. E. Fenimore & M. Galassi, 119–122
- Kippen, R. M., Woods, P. M., Heise, J., in’t Zand, J. J. M., Briggs, M. S., & Preece, R. D. 2003, in *American Institute of Physics Conference Series*, Vol. 662, *Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission*, ed. G. R. Ricker & R. K. Vanderspek, 244–247, arXiv:astro-ph/0203114
- Krimm, H. A., Yamaoka, K., Sugita, S., Ohno, M., Sakamoto, T., Barthelmy, S. D., Gehrels, N., Hara, R., Norris, J. P., Ohmori, N., Onda, K., Sato, G., Tanaka, H., Tashiro, M., & Yamauchi, M. 2009, *ApJ*, 704, 1405
- Lazzati, D., Ghisellini, G., Celotti, A., & Rees, M. J. 2000, *ApJ*, 529, L17
- Lazzati, D., Morsony, B. J., & Begelman, M. C. 2009, *ApJ*, 700, L47
- Liang, E., Kusunose, M., Smith, I. A., & Crider, A. 1997, *ApJ*, 479, L35+
- Lloyd, N. M., & Petrosian, V. 2000, *ApJ*, 543, 722
- Lloyd, N. M., Petrosian, V., & Mallozzi, R. S. 2000, *ApJ*, 534, 227
- Lu, R.-J., Wei, J.-J., Liang, E.-W., Zhang, B.-B., Lü, H.-J., Lian-Zhong, Lü, Lei, W.-H., & Zhang, B. 2012, *ArXiv e-prints*, 1204.0714
- Lyutikov, M. 2009, *ArXiv e-prints*, 0911.0349
- Melandri, A., Mundell, C. G., Kobayashi, S., Guidorzi, C., Gomboc, A., Steele, I. A., Smith, R. J., Bersier, D., Mottram, C. J., Carter, D., Bode, M. F., O’Brien, P. T., Tanvir, N. R., Rol, E., & Chapman, R. 2008, *ApJ*, 686, 1209

- Mészáros, P., & Rees, M. J. 2000, *ApJ*, 530, 292
- Nakar, E., & Piran, T. 2005, *MNRAS*, 360, L73
- Nava, L., Ghirlanda, G., Ghisellini, G., & Celotti, A. 2011, *MNRAS*, 415, 3153
- Nava, L., Ghirlanda, G., Ghisellini, G., & Firmani, C. 2008, *MNRAS*, 391, 639
- Nava, L., Salvaterra, R., Ghirlanda, G., Ghisellini, G., Campana, S., Covino, S., Cusumano, G., D’Avanzo, P., D’Elia, V., Fugazza, D., Melandri, A., Sbarufatti, B., Vergani, S. D., & Tagliaferri, G. 2012, *MNRAS*, 421, 1256
- Pe’er, A., Mészáros, P., & Rees, M. J. 2007, *Royal Society of London Philosophical Transactions Series A*, 365, 1171
- Pe’er, A., & Ryde, F. 2011, *ApJ*, 732, 49
- Pe’er, A., & Zhang, B. 2006, *ApJ*, 653, 454
- Preece, R. D., Briggs, M. S., Mallozzi, R. S., Pendleton, G. N., Paciesas, W. S., & Band, D. L. 1998, *ApJ*, 506, L23
- . 2000, *ApJS*, 126, 19
- Rees, M. J., & Meszaros, P. 1994, *ApJ*, 430, L93
- Sakamoto, T., Hullinger, D., Sato, G., Yamazaki, R., Barbier, L., Barthelmy, S. D., Cummings, J. R., Fenimore, E. E., Gehrels, N., Krimm, H. A., Lamb, D. Q., Markwardt, C. B., Osborne, J. P., Palmer, D. M., Parsons, A. M., Stamatikos, M., & Tueller, J. 2008, *ApJ*, 679, 570
- Sakamoto, T., Lamb, D. Q., Kawai, N., Yoshida, A., Graziani, C., Fenimore, E. E., Donaghy, T. Q., Matsuoka, M., Suzuki, M., Ricker, G., Atteia, J.-L., Shirasaki, Y., Tamagawa, T., Torii, K., Galassi, M., Doty, J., Vanderspek, R., Crew, G. B., Villasenor, J., Butler, N., Prigozhin, G., Jernigan, J. G., Barraud, C., Boer, M., Dezalay, J.-P., Olive, J.-F., Hurley, K., Levine, A., Monnelly, G., Martel, F., Morgan, E., Woosley, S. E., Cline, T., Braga, J., Manchanda, R., Pizzichini, G., Takagishi, K., & Yamauchi, M. 2005, *ApJ*, 629, 311
- Shahmoradi, A., & Nemiroff, R. J. 2009, *ArXiv e-prints*, 0904.1464
- Stern, B. E., & Poutanen, J. 2004, *MNRAS*, 352, L35
- Tavani, M. 1996, *ApJ*, 466, 768

Titarchuk, L., Farinelli, R., Frontera, F., & Amati, L. 2012, *ApJ*, 752, 116

Yonetoku, D., Murakami, T., Nakamura, T., Yamazaki, R., Inoue, A. K., & Ioka, K. 2004, *ApJ*, 609, 935

Yonetoku, D., Murakami, T., Tsutsui, R., Nakamura, T., Morihara, Y., & Takahashi, K. 2010, *PASJ*, 62, 1495

Table 1. GRB Sample Chosen for the Time-Resolved Spectral Analysis

GRB	Redshift	Fluence ($\times 10^{-6}$ cgs)	No. of Intervals	No. of Useful Intervals
970111	–	39.18 ± 0.08	10	8
980329	–	37.53 ± 0.07	8	6
990123	1.60	205.12 ± 0.03	26	19
990510	1.619	15.80 ± 0.07	15	8

Note. — For each GRB we report the redshift, the fluence in the 2-2000 keV energy band, the number of time intervals in which we subdivided the time profile and those used in the time-resolved spectral analysis.

Table 2. Best fit Parameters of the BF in the Time Intervals for Which a Sensitive Spectral Analysis Was Possible

GRB	Interval	Start (Δt) (SOD)	α	β	E_p (keV)	χ^2/dof	Flux ($\times 10^{-6}$ cgs)
970111	3	35045.0 (3)	$0.57^{+0.08}_{-0.06}$	$-3.99^{+0.32}_{-0.43}$	203^{+8}_{-7}	114.2/97	1.98 ± 0.55
	4	35048.0 (6)	$-0.23^{+0.06}_{-0.02}$	$-4.89^{+0.77}_{-5.11}$ a	174^{+3}_{-8}	87.2/75	1.79 ± 0.20
	5	35054.0 (3)	$-0.32^{+0.05}_{-0.03}$	$-9.37^{+4.35}_{-0.63}$ a	162^{+5}_{-2}	89.2/73	2.39 ± 0.18
	6	35057.0 (5)	$-0.48^{+0.03}_{-0.03}$	$-4.94^{+0.56}_{-5.06}$ a	151^{+4}_{-3}	83.0/73	2.44 ± 0.16
	7	35062.0 (3)	$-0.58^{+0.04}_{-0.04}$	$-3.46^{+0.15}_{-0.21}$	89^{+4}_{-3}	29.3/13	1.02 ± 0.14
	8	35065.0 (4)	$-0.58^{+0.02}_{-0.03}$	$-3.74^{+0.21}_{-0.23}$	64^{+2}_{-2}	32.3/13	0.58 ± 0.07
	9	35069.0 (4)	$-0.61^{+0.08}_{-0.06}$	$-3.15^{+0.09}_{-0.09}$	56^{+5}_{-6}	15.6/12	0.71 ± 0.38
	10	35073.0 (13)	$-0.69^{+0.04}_{-0.05}$	$-2.85^{+0.08}_{-0.07}$	57^{+5}_{-3}	22.4/13	0.43 ± 0.15
980329	2	13477.0 (4)	$-0.74^{+0.09}_{-0.07}$	$-2.17^{+0.10}_{-0.12}$	256^{+35}_{-32}	105.7/83	1.50 ± 0.49
	3	13481.0 (2)	$-0.61^{+0.06}_{-0.05}$	$-2.46^{+0.08}_{-0.10}$	236^{+19}_{-9}	108.1/90	3.25 ± 0.66
	4	13483.0 (3)	$-0.70^{+0.03}_{-0.05}$	$-2.49^{+0.06}_{-0.05}$	235^{+16}_{-9}	105.9/97	4.82 ± 0.70
	5	13486.0 (4)	$-0.80^{+0.05}_{-0.02}$	$-2.22^{+0.04}_{-0.04}$	242^{+8}_{-17}	135.5/105	4.25 ± 0.41
	6	13490.0 (4)	$-1.21^{+0.05}_{-0.05}$	$-2.22^{+0.07}_{-0.09}$	169^{+21}_{-19}	97.7/77	0.95 ± 0.15
	7	13494.0 (19)	$-1.49^{+0.07}_{-0.05}$	$-2.79^{+0.46}_{-7.21}$ a	136^{+32}_{-23}	52.8/47	0.15 ± 0.04
990123	2	35221.9 (6)	$-0.44^{+0.13}_{-0.11}$	$-9.37^{+6.56}_{-0.63}$ a	148^{+32}_{-34}	39.2/35	0.22 ± 0.13
	3	35227.9 (6)	$-0.19^{+0.10}_{-0.32}$	$-2.52^{+0.40}_{-7.48}$ a	171^{+97}_{-25}	27.8/44	0.64 ± 0.49
	4	35233.9 (2)	$-0.58^{+0.12}_{-0.11}$	$-9.30^{+6.70}_{-0.70}$ a	388^{+96}_{-49}	55.1/57	1.71 ± 0.90
	5	35235.9 (2)	$-0.55^{+0.03}_{-0.03}$	$-9.37^{+6.96}_{-0.63}$ a	598^{+52}_{-53}	101.9/105	3.80 ± 0.83
	6	35237.9 (2)	$-0.56^{+0.03}_{-0.08}$	$-2.07^{+0.39}_{-7.92}$ a	844^{+251}_{-145}	152.8/151	8.64 ± 3.01
	7	35239.9 (2)	$-0.55^{+0.03}_{-0.04}$	$-2.12^{+0.19}_{-0.71}$	979^{+149}_{-97}	177.3/182	13.87 ± 2.60
	8	35241.9 (2)	$-0.54^{+0.02}_{-0.04}$	$-2.29^{+0.28}_{-7.72}$ a	1094^{+220}_{-108}	164.7/183	14.70 ± 2.91
	9	35243.9 (2)	$-0.51^{+0.04}_{-0.06}$	$-1.98^{+0.13}_{-0.37}$	594^{+130}_{-64}	192.0/166	8.58 ± 2.41
	10	35245.9 (2)	$-0.56^{+0.02}_{-0.03}$	$-9.37^{+5.36}_{-0.62}$ a	478^{+28}_{-22}	149.3/140	5.19 ± 0.68
	11	35247.9 (2)	$-0.66^{+0.07}_{-0.04}$	$-3.66^{+1.10}_{-6.33}$ a	272^{+30}_{-40}	98.9/104	2.12 ± 0.61
	12	35249.9 (2)	$-0.51^{+0.05}_{-0.04}$	$-9.36^{+6.04}_{-0.63}$ a	431^{+39}_{-29}	136.5/118	4.35 ± 0.81
	13	35251.9 (2)	$-0.44^{+0.05}_{-0.04}$	$-2.28^{+0.18}_{-0.29}$	582^{+65}_{-64}	211.4/188	9.53 ± 2.11
	14	35253.9 (2)	$-0.58^{+0.04}_{-0.03}$	$-2.27^{+0.20}_{-0.35}$	712^{+63}_{-69}	200.0/180	9.84 ± 1.67
	15	35255.9 (2)	$-0.61^{+0.04}_{-0.03}$	$-2.44^{+0.25}_{-0.30}$	610^{+41}_{-69}	169.1/182	7.54 ± 1.26
	16	35257.9 (2)	$-0.71^{+0.04}_{-0.04}$	$-2.77^{+0.40}_{-7.23}$ a	478^{+60}_{-52}	140.6/125	5.13 ± 1.09

Table 2—Continued

GRB	Interval	Start (Δt) (SOD)	α	β	E_p (keV)	χ^2/dof	Flux ($\times 10^{-6}$ cgs)
	17	35259.9 (5)	$-0.91^{+0.02}_{-0.03}$	$-3.29^{+0.67}_{-6.71}\text{a}$	414^{+34}_{-34}	160.5/170	3.02 ± 0.42
	18	35264.9 (5)	$-1.01^{+0.03}_{-0.03}$	$-2.00^{+0.12}_{-0.19}$	260^{+50}_{-37}	164.4/147	2.16 ± 0.42
	19	35269.9 (5)	$-1.08^{+0.03}_{-0.03}$	$-2.62^{+0.56}_{-7.37}\text{a}$	361^{+57}_{-55}	140.8/147	1.96 ± 0.37
	20	35274.9 (5)	$-1.13^{+0.01}_{-0.03}$	$-9.36^{+6.79}_{-0.64}\text{a}$	406^{+70}_{-46}	112.9/134	1.73 ± 0.28
990510	1	31745.9 (5)	$-0.67^{+0.09}_{-0.09}$	$-2.89^{+0.15}_{-0.28}$	80^{+9}_{-10}	73.9/48	0.42 ± 0.16
	2	31750.9 (5)	$-0.96^{+0.12}_{-0.07}$	$-3.55^{+0.33}_{-1.63}$	86^{+7}_{-9}	53.4/53	0.54 ± 0.20
	6	31770.9 (15)	$-0.97^{+0.07}_{-0.06}$	$-2.60^{+0.22}_{-0.38}$	264^{+34}_{-34}	95.3/81	1.29 ± 0.40
	7	31785.9 (5)	$-0.80^{+0.08}_{-0.06}$	$-2.57^{+0.10}_{-0.11}$	178^{+14}_{-17}	100.3/80	2.05 ± 0.63
	8	31790.9 (3)	$-1.14^{+0.03}_{-0.04}$	$-9.37^{+6.31}_{-0.63}\text{a}$	151^{+13}_{-11}	70.9/62	0.63 ± 0.13
	9	31793.9 (4)	$-1.01^{+0.18}_{-0.35}$	$-2.35^{+0.05}_{-0.06}$	31^{+71}_{-10}	28.7/39	1.07 ± 1.03
	10	31797.9 (5)	$-1.14^{+0.05}_{-0.12}$	$-2.86^{+0.11}_{-0.12}$	64^{+2}_{-5}	20.0/16	0.45 ± 0.13
	11	31802.9 (4)	$-1.70^{+0.10}_{-0.05}$	$-9.37^{+6.58}_{-0.63}\text{a}$	49^{+11}_{-11}	40.9/34	0.11 ± 0.04

Note. — Uncertainties are single parameter errors at 90% confidence level. For each time interval of Figure 1, we also report the Seconds Of Day (SOD) in correspondence of its start, its duration Δt in seconds, and the corresponding flux in the 2–2000 keV energy band. For the flux estimate, in the cases the high energy index β could not be constrained, it was frozen to -2.3 .

^aValue fixed to -2.3 in the computation of flux and luminosity.

Table 3. Correlation Analysis Results between E_p and 2–2000 keV Flux

GRB	ρ	NHP	k	m	σ_{ext}	χ_r^2 (dof)
970111	0.69	5.0×10^{-2}	6.05 ± 0.34	0.68 ± 0.06		2.9 (6)
			$5.91^{+0.91}_{-0.78}$	$0.65^{+0.16}_{-0.14}$	$0.04^{+0.05}_{-0.03}$	1.5 (5)
980329	0.49	0.32	3.25 ± 0.26	0.16 ± 0.04		1.2 (4)
			$3.20^{+0.43}_{-0.40}$	$0.15^{+0.08}_{-0.07}$	$0.00^{+0.04}_{-0.00}$	1.6 (3)
990123	0.92	2.68×10^{-8}	5.51 ± 0.28	0.53 ± 0.05		1.3 (17)
			$5.16^{+0.49}_{-0.48}$	$0.46^{+0.09}_{-0.09}$	$0.04^{+0.11}_{-0.04}$	1.1 (16)
990510	0.88	3.85×10^{-3}	7.09 ± 1.01	0.81 ± 0.15		1.8 (6)
			$5.54^{+1.55}_{-1.43}$	$0.56^{+0.25}_{-0.23}$	$0.09^{+0.10}_{-0.09}$	1.4 (5)

Note. — A power-law relation between the two parameters is assumed: $\log E_p = k + m \log flux$. In addition to the best fit parameters k and m , reported are the Spearman correlation coefficient ρ , NHP, and the best fit χ_r^2 with the degrees of freedom dof. The parameter estimate was performed using both the least-squares method and the likelihood method, in which case the extrinsic variance σ_{ext} between the $E_{p,i}$ and flux is included in the log-likelihood function as a free parameter(see the text).

Table 4. Correlation Analysis Results between the Intrinsic (Redshift Corrected) Peak Energy $E_{p,i}$ and the GRB Luminosity, Either for Individual GRBs with Known Redshift (990123, 990510) or When All the Data Points of These GRBs Are Taken Into Account

GRB	ρ	NHP	k	m	σ_{ext}	χ_r^2 (dof)
990123	0.92	2.7×10^{-8}	2.64 ± 0.05	0.53 ± 0.05		1.3 (17)
			$2.71^{+0.09}_{-0.09}$	$0.46^{+0.09}_{-0.09}$	$0.04^{+0.11}_{-0.04}$	1.1 (16)
990510	0.88	3.85×10^{-3}	2.46 ± 0.04	0.81 ± 0.15		1.8 (6)
			$2.45^{+0.08}_{-0.09}$	$0.56^{+0.25}_{-0.23}$	$0.09^{+0.10}_{-0.09}$	1.4 (5)
full sample	0.94	1.57×10^{-13}	2.51 ± 0.03	0.66 ± 0.03		1.6 (25)
			$2.53^{+0.06}_{-0.06}$	$0.63^{+0.06}_{-0.07}$	$0.06^{+0.05}_{-0.06}$	1.2 (24)

Note. — A power-law relation between the two parameters is assumed: $\log E_{p,i} = k + m \log L_{iso}$. In addition to the best fit parameters k and m , reported are the Spearman correlation coefficient ρ , NHP, and the best fit reduced χ_r^2 with dof. The parameter estimate was performed using both the least-squares method and the likelihood method, in which case the extrinsic variance σ_{ext} between the $E_{p,i}$ and flux is included in the log-likelihood function as a free parameter(see the text).

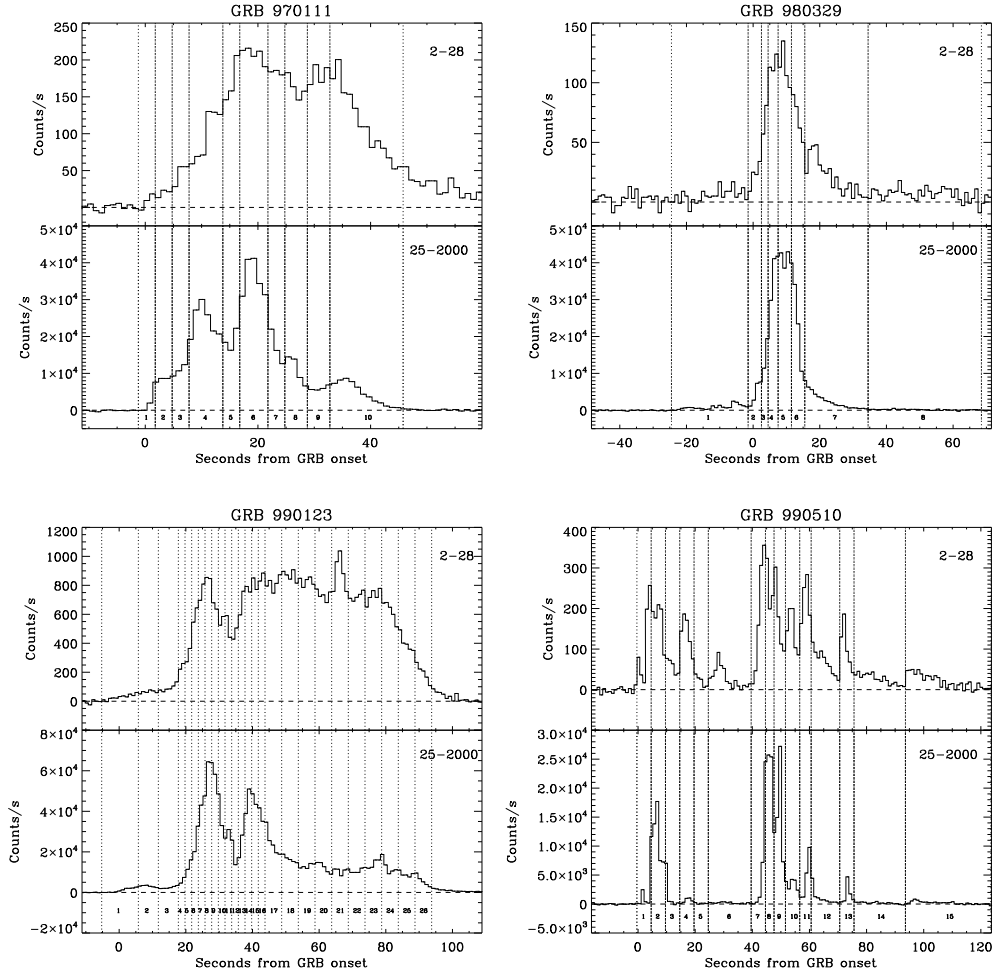


Fig. 1.— Light curves of GRBs 970111, 980329, 990123, and 990510, detected with *Bep-poSAX* WFC (2–28 keV) and *BATSE* (25–2000 keV). Also shown are the intervals in which the time resolved spectra were derived.

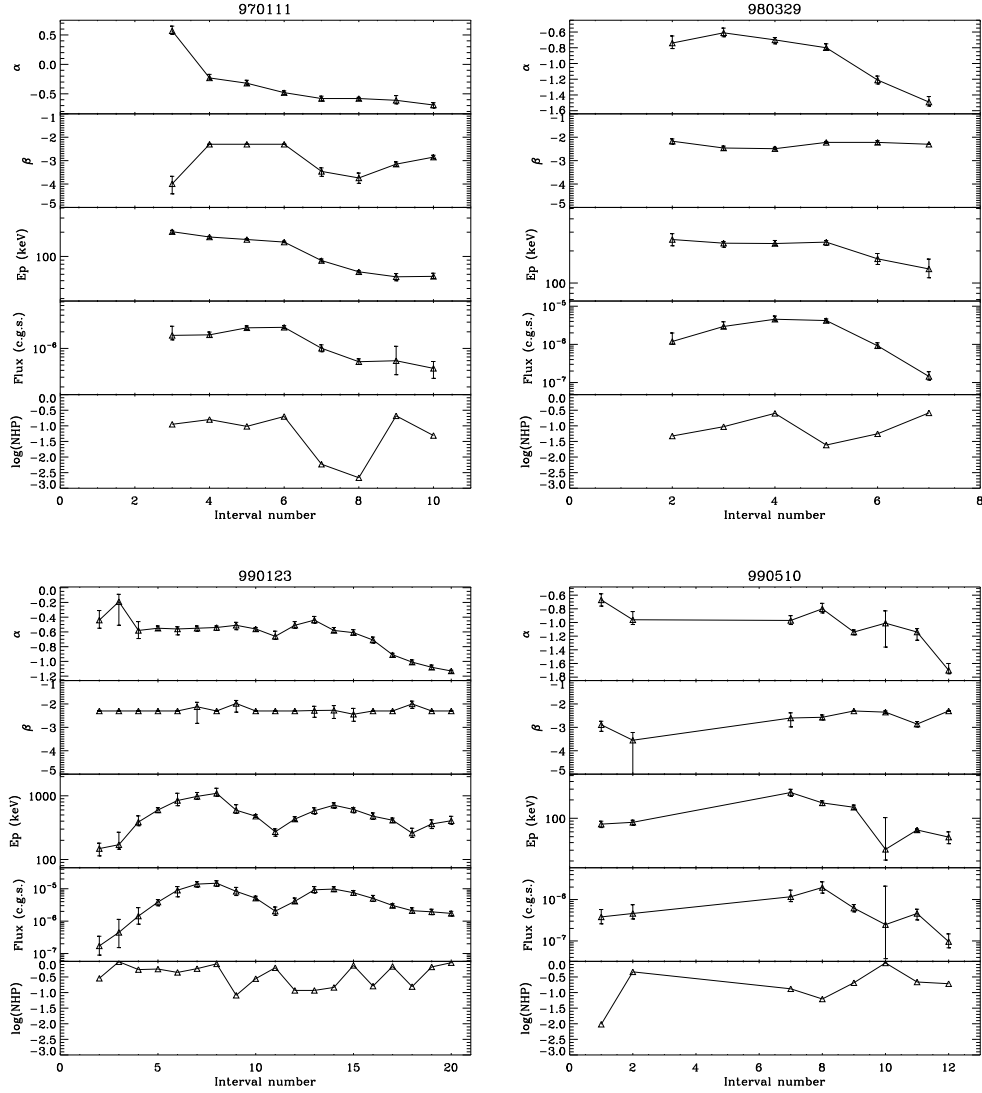


Fig. 2.— Temporal evolution of the BF best fit parameters and of the null hypothesis probability (NHP), for each of the GRBs 970111, 980329, 990123, 990510. Top panel: low energy PL index α . Second panel from the top: high energy power-law index β , in the cases in which it was constrained from the fit. In the other cases (not plotted) a value of $\beta = -2.3$ is assumed. Third panel from the top: peak energy E_p . Fourth panel from the top: estimated 2–2000 keV flux. Bottom panel: null hypothesis probability (NHP) for the tested function.

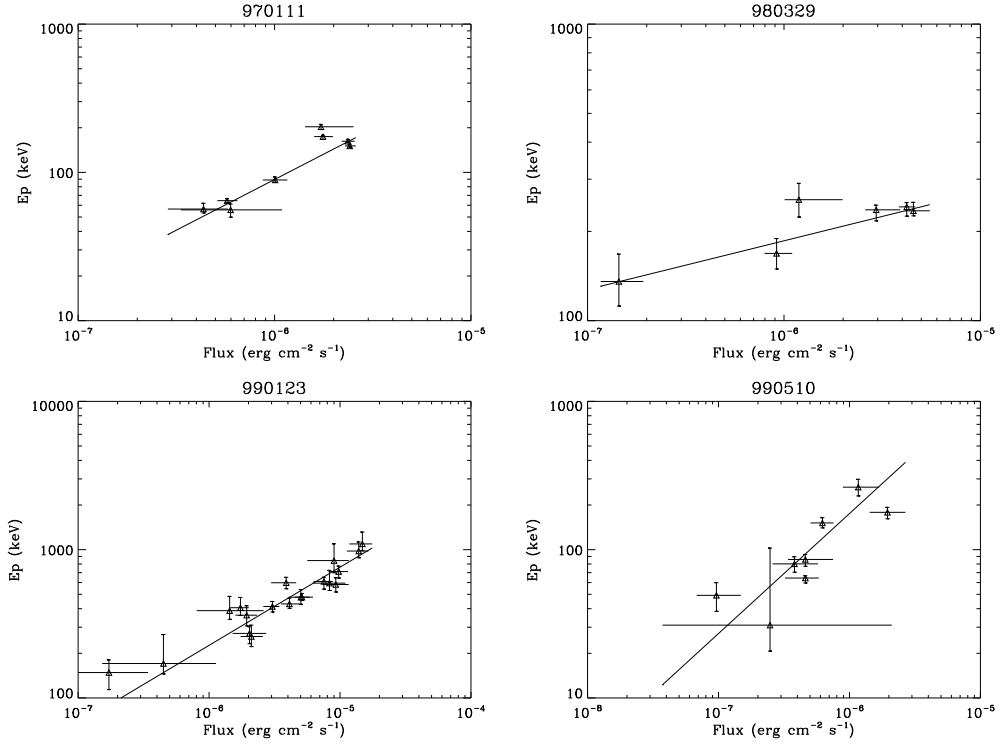


Fig. 3.— Dependence of the time resolved peak energy, obtained from the best fit of the BF to the joint WFC+*BATSE* spectra, on the 2–2000 keV flux measured in the corresponding interval. Also shown is the best fit power-law curve.

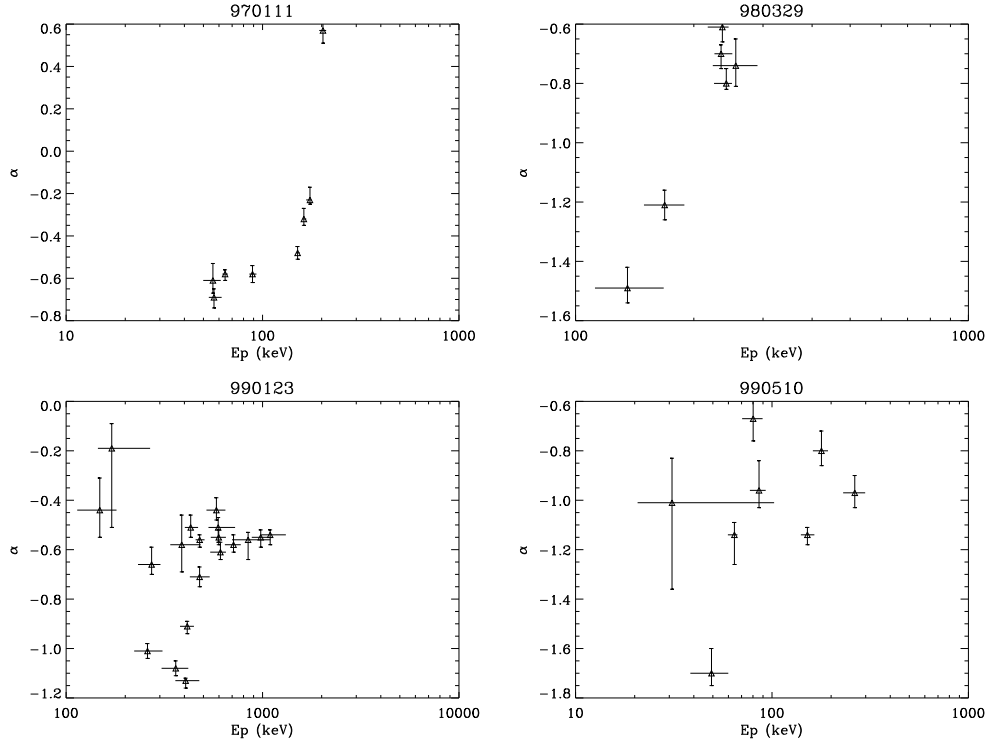


Fig. 4.— Behavior of the time-resolved low-energy photon index, obtained from the best fit of the BF to the joint WFC+*BATSE* spectra, with the corresponding E_p derived in the same spectral interval.

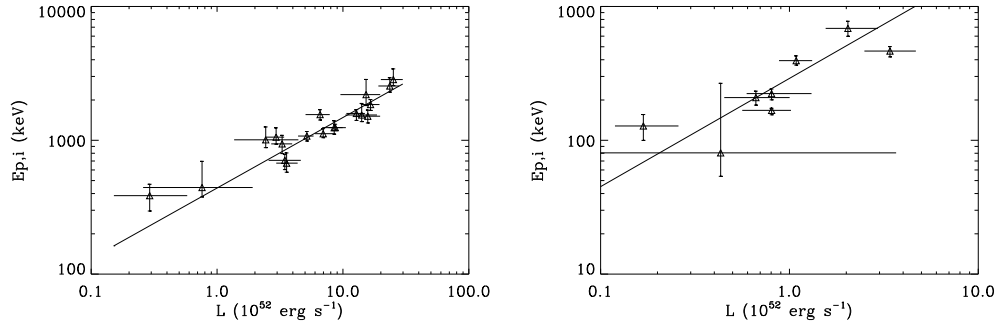


Fig. 5.— Intrinsic $E_{p,i}$ as a function of the 2–2000 keV luminosity for GRBs 990123 and 990510.

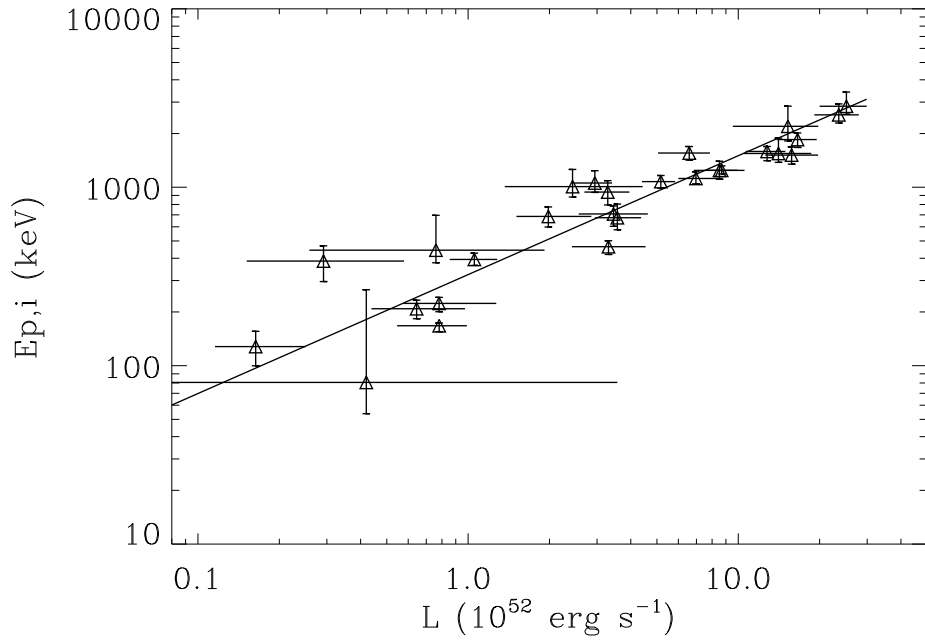


Fig. 6.— Intrinsic $E_{p,i}$ as a function of the 2–2000 keV isotropic luminosity L_{iso} , obtained by merging together all the available data for GRB 990123 and GRB 990510. The continuous line shows the best fit power-law slope (see Table 4).

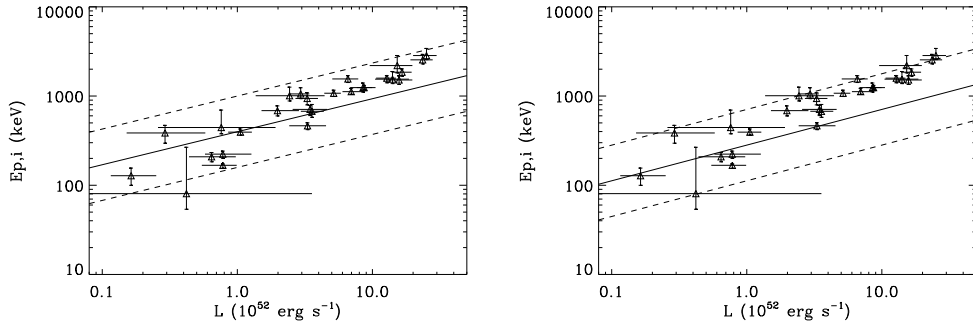


Fig. 7.— Comparison of the derived $E_{p,i}$ versus L_{iso} with the results reported by Ghirlanda et al. (2010). Left panel: our results compared with the best-fit power-law (continuous line) and the 2σ belt (dashed lines) obtained using 51 time-resolved spectra extracted from eight GRBs observed with *Fermi*. Right panel: our results compared with the best-fit power-law (continuous line) and the 2σ belt (dashed lines) obtained by Ghirlanda et al. (2010), using time-averaged spectra of 105 (pre-*Fermi* plus *Fermi*) events.